Spatial Statistics of Deep-Water Ambient Noise; Dispersion Relations for Sound Waves and Shear Waves

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LONG-TERM GOALS

1) Deep-water ambient noise Profile the spectral, temporal and spatial properties of broadband (3 Hz – 30 kHz) ambient noise from the sea surface to the seabed in the deep ocean trenches. Develop theoretical models of the second-order spatial statistics of the noise. New focus is on the deepest part of the ocean, the Challenger Deep in the Mariana Trench.

2) Marine sediment acoustics Develop a unified, physics-based model of sound wave and shear wave propagation in saturated, unconsolidated marine sediments. New focus is on very fine-grained sediments (silt and clay).

OBJECTIVES

1) The scientific objective of the deep-water ambient noise research is to measure the second-order spatial statistics of the ambient noise in the deep ocean trenches as a function of depth, from the sea surface to the seabed. Regions of interest include the Mariana Trench, notably the Challenger Deep (11 km), the Tonga Trench (9 km), and the Puerto Rico Trench (8 km). Environmental and system data will also be depth-profiled, including temperature, salinity, pressure and (directly measured) sound speed, along with all system motions (translational and rotational). Theoretical modeling of the spectral, spatial and temporal properties of the ambient noise will also be performed.

2) The sediment acoustics research is aimed at developing a unified theory of wave propagation in marine sediments in the form of the dispersion relations for the compressional and shear waves. Besides the frequency dependencies of the wave speeds and attenuations, these expressions will also return the dependence of the wave parameters on the mechanical properties of the sediment, namely porosity, density, grain size and overburden pressure. A new focus is on the inter-particle cohesive forces in silts and clays and their role in controlling wave speeds and attenuations. On a quantum mechanical level, these forces are the result of molecular and electrostatic interactions,

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and include van der Waals forces, whilst on a larger scale capillarity and excess charges play important roles in the cohesion of the particles.

APPROACH

1) Deep-water ambient noise Three deep-diving, autonomous instrument platforms, known as Deep Sound I, II, & III, have been designed and built by my research group. Deep Sound consists of a Vitrovex glass sphere housing a microprocessor for system control, along with data acquisition and storage electronics. External to the sphere are several hydrophones (bandwidth 3 Hz – 30 kHz, calibrated to equivalent depths of 12 km), which may be arranged in various vertical and horizontal configurations, and an environmental sensor package [Conductivity-Temperature-Depth sensor (CTD) plus sound speed sensor (SVX)]. The system is untethered, descending under gravity and, after releasing a drop weight at a pre-assigned depth, returning to the surface under buoyancy. Throughout the descent and ascent, at a nominal 0.5 m/s, acoustic and environmental data are continuously recorded. Three beacons (a high intensity strobe, a radio antenna, and an Argos GPS) aid recovery of the system. Several fail-safe devices ensure that the weight is indeed dropped, thus allowing the system to return to the surface.

   In support of the ambient noise experiments using the Deep Sound systems, a series of analytical models for the spatial coherence and cross-correlation properties of ambient noise in the deep ocean is being developed. These models address the vertical and horizontal directionality of the noise and their relationships to the coherence function and the cross-correlation function. The models will help in interpreting the two-point measurements of noise recovered from the Deep Sound systems.

2) Marine sediment acoustics The theoretical approach, which has come to be known as the grain-shearing (GS) theory, is based on the idea that the dispersion and attenuation of compressional and shear waves in unconsolidated porous media, such as marine sediments, are governed by inter-granular interactions. The two-phase unconsolidated granular material is treated as a continuum in which, during the passage of a wave, internal stresses are present, associated with micro-roughness in the form of asperities on the surfaces of contact of the grains. Compressional and shear waves are represented by (time domain) wave equations, derived from the Navier-Stokes equation, taking account of the stresses that are present at the inter-granular contacts. These wave equations contain convolutions of partial-differential terms representing dissipation and dispersion due to the mechanism of strain-hardening. As the grains slide against one another during the passage of a wave, the strain-hardening interaction becomes progressively stiffer until eventually the motion ceases. Although, on a microscopic level, this is a non-linear mechanism, the associated wave equations are linear. The compressional and shear dispersion relations that derive from the GS wave equations take the form of closed form algebraic expressions. The GS theory is the basis for new research on very fine-grained sediments (silts and clays), in which inter-granular cohesion is governed by a number of forces, including capillarity and forces associated with quantum mechanical interactions (van der Waals forces).

WORK COMPLETED

Three versions of Deep Sound, designated the Marks. I, II and III, have been designed and built. Each evolution of the system has progressively more instrumentation onboard. Deep Sound Mark I, which

has been deployed a number of times to great depths, has now been retired from service and is no longer operational.

Deep Sound Mark II was deployed in the Mariana Trench in November 2009, where it successfully recorded ambient noise on vertically and horizontally aligned hydrophones from the surface to a depth of 9 km over the acoustic frequency band from 3 Hz to 30 kHz.

Deep Sound Mk. III is the most sophisticated of the three systems, capable of descending to a depth of 11 km. On board is a sound speed sensor (SVX), a sing-around instrument that records the speed of sound directly, for comparison with the computed values from the CTD. This allows us to test the validity of sound speed algorithms for the extreme pressures found at the bottom of ocean trenches.

An attempt was made to deploy Deep Sound II and III in the Mariana Trench in July 2011, to depths of 9 km and 11 km, respectively. Working with a National Geographic group, a research vessel, the M/V Super Emerald, was chartered out of Saipan (at no cost to us) and used for the four-day deployment. However, severe weather in the form of Typhoon Mufia prohibited the deployment of any of the Deep Sound systems. Moreover, the M/V Super Emerald was not well suited to the task, and at least one system (not one of ours) was lost. We should have been the last to deploy but decided against putting our systems in the water, given the extreme problems that the other groups had experienced.

In early September 2012, Deep Sound Marks II & III were deployed in the Tonga Trench from the R/V Roger Revelle. The hydrophones on board each of the systems were fitted with newly designed flow shields, intended to suppress the effects of turbulent flow generated by the motion of Deep Sound through the water column. Both Deep Sound systems descended to a depth of 8.5 km, stayed on the bottom for extended periods (20 minutes for Mark II and 3 hours for Mark III), and then returned to the surface, all the while collecting broadband (3 Hz – 30 kHz) ambient noise data, along with environmental and system data.

An invited paper[1] on Deep Sound has been published in a special issue of the *Journal of the Marine Technology Society* commemorating the Golden Anniversary of the dive of the manned submersible *Trieste* to the bottom of the Challenger Deep. A theoretical paper[2] on the directionality of ambient noise and its effects on the two point (vertical and horizontal) cross-correlation function has been published in the *Journal of the Acoustical Society of America* (JASA). Another paper[3] has been published in JASA in which a theoretical model of a three–dimensional noise field is developed. The model represents noise from a storm, showing a strong peak in the horizontal combined with significant vertical directionality. This is relevant to some of the data that were collected in the Philippine Sea by Deep Sound Mark I as an intense storm passed more or less overhead. An analysis of the storm data is described in a recently published paper[4] in JASA. Wind-driven noise, also recorded during one of the deployments of Deep Sound Mark I in the Philippine Sea, is described in another paper[5] that recently appeared in JASA. A theoretical paper[6] has been published in JASA on band-limited noise, and the effects the filtering has on the cross-correlation function.

At great depth and at sufficiently high frequencies, the effect of attenuation on the directionality of wind driven ambient noise should be detectable. This operating regime is within the capabilities of Deep Sound. To help extract the effects of attenuation from the noise data, a theoretical model of wind-driven ambient noise in an attenuating ocean[7] has been developed and has been recently published in JASA.

An analysis of the Deep Sound III ambient noise data from the bottom of the Tonga Trench has been performed and reported in a paper that has been accepted for publication[8] in JASA.

Turning to wave propagation in porous materials, an analysis of shear wave propagation in sandy sediments has been performed in which the shear attenuation predicted by the GS theory is compared with all the available data sets in the literature on shear attenuation as a function of frequency. A paper on this analysis has been accepted for publication[9] in JASA. A related paper, on evaluating the shear visco-mechanical time constant, is currently under review for publication[10] in JASA.

RESULTS

While Deep Sound III was on the bottom of the Tonga Trench, at a depth of 8,515 m, it recorded the ambient noise on four hydrophones, three aligned vertically and two horizontally. The two times series from the horizontal alignment allowed the horizontal coherence function and the associated cross-correlation function to be computed. The cross-correlation function, shown in Fig. 1, exhibits features indicating that the noise field was non-uniform in azimuth. The asymmetry in the two peaks labeled A_1 and A_2 is associated with highly directional noise arrivals from the support vessel, the R/V Roger Revelle, which was standing off 12.3 km to the south of the experiment site. The bathymetric trough depicted in the figure is due to shadowing of the wind-generated noise by the walls of the Tonga Trench: more noise propagates along the axis of the trench than normal to the axis. This effect has been modeled using a von Mises circular distribution function from directional statistics[3, 8], yielding the horizontal cross-correlation function represented by the smooth black line in Fig. 1.

With regard to sediments, all the available data sets on the frequency dependence of the shear attenuation have been carefully examined and compared with the predictions of the grain-shearing theory. The data, all from laboratory experiments, relate to sands and glass beads, saturated and dry. In all cases, the theory accurately matches the frequency-dependent data[9], once random fluctuations have been suppressed by averaging over several realizations of similar materials. This reduces the variability associated with compaction, the orientation of the grains, and other factors.

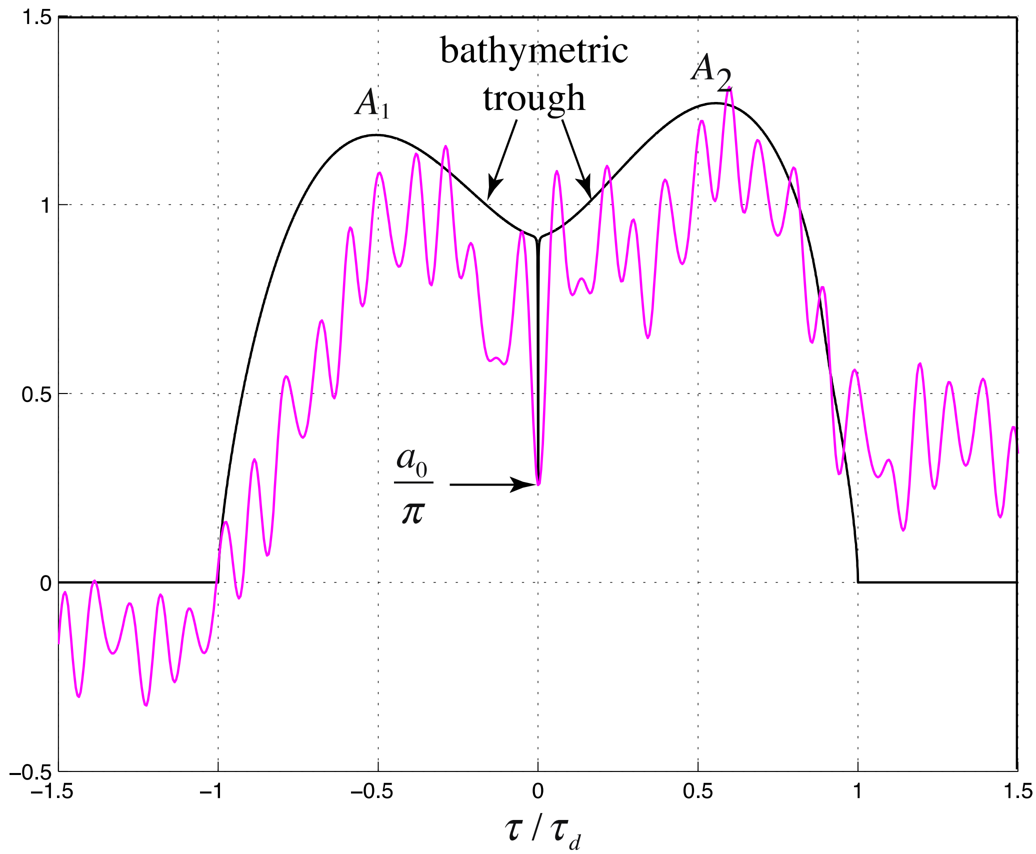

Fig. 1 Horizontal cross-correlation function from Deep Sound III at a depth of 8,515 m in the Tonga Trench. The magenta line represents the data from the horizontally aligned hydrophone pair and the smooth black line is from a von Mises representation of the horizontal directionality of the noise field.

IMPACT/APPLICATIONS

Deep Sound Mark III is a modular system, allowing the hydrophones in the current configuration to be replaced with any other type of sensor, for instance, dissolved oxygen, carbon dioxide or hydrocarbon sensors. Mark III can even profile the local current vector, since the onboard inertial navigation system (INS) tracks translational and rotational motion due to advection from the current.

My theory of wave propagation in marine sediments[11] has a variety of applications, particularly in regard to acoustic inversions for the geo-acoustic parameters of the seabed. Charles Holland and Ross Chapman are independently using the theory to develop numerical inversion schemes for recovering the properties of the bottom. It should also play a central role in future research projects aimed at understanding wave propagation in very fine-grained sediments, that is, silts and clays.

Michael Porter is developing a suite of 3-D acoustic propagation models. He is using my analytical models[12, 13] of the penetrable wedge and the conical seamount, both developed some years ago, for comparison with his numerical results.

A conference was held recently on “Basic Science and the Future Warfighter” [ASD(R&E) Basic Science/Labs, Arlington, VA July 30-31 2012]. One of the prominent ideas discussed was the use of low-flying aircraft as sources of sound for underwater acoustics applications, including target detection and bottom characterization, as investigated theoretically and experimentally by my research group at SIO over recent years[14]. We are planning a research project on helicopter noise, which is also relevant in the same context.

TRANSITIONS

As previously reported.

RELATED PROJECTS

As previously reported.

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PUBLICATIONS
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1. S. E. Freeman, M. J. Buckingham, L. A. Freeman, M. O Lammers and G. L. D'Spain, "Cross correlation triangulation and curved-wavefront focusing using a horizontal bi-linear hydrophone array to locate biological sound sources on a coral reef", *J. Acoust. Soc. Am.* **in review** (2014) [refereed].
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7. D. R. Barclay and M. J. Buckingham, "Depth dependence of the power spectral density and vertical directionality of rain noise in the Philippine Sea", *J. Acoust. Soc. Am.*, **133**, 2576-2585 (2013) [published, refereed]
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PATENTS

As previously reported.

HONORS/AWARDS/PRIZES

1. Member of the Scientific Committee, 2nd Conference on Underwater Acoustics, Rhodes, Greece, 22 – 27 June 2014.
2. Invited Lecturer, ASA School, 167th Meeting of the Acoustical Society of America, Providence, Rhode Island, 3 & 4 May 2014.
3. Member of the Advisory Committee, 11th International Conference on Theoretical and Computational Acoustics (ICTCA), College Station, Texas 10 – 14 March 2014.
4. Keynote lecturer, "Sound propagation in unconsolidated marine sediments" 11th International Conference on Theoretical and Computational Acoustics, College Station, Texas, 11 March 2014.
5. My graduate student, Simon Freeman, won Outstanding Student Paper Award for "Array-based hydroacoustic characterization of P, S, and T-phases in the Philippine Sea", Ocean Sciences section, American Geophysical Union Fall meeting, 9-13 December 2013.
6. My graduate student, Simon Freeman, successfully defended his Ph.D. thesis, 26 November 2013.
7. Member of the Scientific Committee, 1st International Conference on Underwater Acoustics, Corfu, Greece, 23 – 28 June 2013.
8. Chair, Session 4aNSb – Future of Acoustics, ICA/ASA Montreal, 6 June 2013.
9. Member of the Executive Council, Acoustical Society of America, 2010 – 2013.
10. Chair, External Affairs committee, Acoustical Society of America, 2012-2013.
11. General Chair, 162nd Meeting of the Acoustical Society of America, San Diego, California, Fall 2011.